Schardt SG

National Aeronautics and Space Administration
Goddard Space Flight Center
Contract No. NAS-5-3760

ST - AI - MHD - 10 434

TO THE THEORY OF SHIFTING IONOSPHERE DISTURBANCES (MAGNETOHYDRODYNAMIC ABSORPTION)

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FACILITY FORM 602

N66-86510
(ACCESSION NUMBER)

11
(PAGES)

CR 77685
(NASA CR OR TMX OR AD NUMBER)

(THRU)

None
(CODE)

(CATEGORY)

5 January 1966

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Geomagnetizm i Aeronomiya
Tom 5, No. 5, 843-849,
Izdatel'stvo "NAUKA", 1965

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SUMMARY

The magnetohydrodynamic absorption of inner gravitational waves is investigated under conditions of the F-layer of the ionosphere. The calculations, conducted in their application to shifting ionosphere disturbances, show that this absorption is substantial, in particular during the daytime hours in the altitudes near 300 km.

* * *

When investigating large-scale irregularities of the electron concentration in the F-layer, effects related to the so-called shifting diturbances were already revealed as far back as in 1948 - 1949. Characteristic for these disturbances are the displacements in the horizontal direction with velocities $\sim 150 - 200$ m/sec to distances of several thousand kilometers. It is natural to relate these displacements with the propagation in the ionosphere of a specific type of waves. We shall assume for such a type of waves the inner gravitational waves. This viewpoint was expressed at first by Martin [1] and it was afterward developed at further length by Hines [2]. The Martin-Hines theory is good agreement with the basic observation data on shifting disturbances [2 – 4].

The propagation conditions in the ionosphere of inner waves were analyzed in detail in the works [1 – 2]. At the same time, the analysis of questions linked with the absorption of these waves cannot be considered as exhausted. Conducted were only the estimates of absorption on account of viscosity [2, 5, 6]] The viscous dissipation limits the possibility of

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* K TEORII PEREMESHCHAYUSHCHIKHSYA IONOSFERNYKH VOZMUSHCHENIY (MAGNITOGIDRODINAMICHESKOYE POGLOSHCHENIYE).

propagation of irregularities with comparatively small wavelength, from ~ 30 to 90 km [2, 6]. For a more widespread type of disturbances with $\lambda \sim 200 - 500$ km [2] the influence of viscosity (heat conductivity) at heights below the F-layer maximum is of little effectiveness. Here the dissipation mechanism, linked with the induction deceleration at motion of a conducting medium across the magnetic field, becomes significant. We shall call this absorption mechanism the magnetohydrodynamic absorption. The computations of such a type of absorption were conducted more than once for problems of dynamics of a conducting fluid [7, 8]. In its application to the ionosphere, the absorption of purely acoustic waves was determined in [9]. However, because of failure to account for the force of gravitation in the latter, we can not make use of its conclusions.

Our fundamental problem consists in the determination of the value of the magnetohydrodynamic absorption of inner waves in the ionosphere, applying it to the problem of shifting disturbances. In its general context such a computation for an incompletely ionized gas of the ionosphere type would be beset with great difficulties. However, bearing in mind that, as a rule, shifting disturbances are registered in the E-layer, the whole consideration may be considerably simplified.

We shall present in #1 the basic equations and the calculation of the magnetohydrodynamic absorption of inner waves in the F-layer. The application of the results obtained to shifting disturbances will be given in #2. Calculations show that for the latter the absorption is essential and its presence must be taken into account.

#1. - Inner Gravitational Waves in the F-layer. When investigating the propagation and absorption of inner waves of small amplitude, it is necessary to start from the following system of linearized equations:

$$\rho_0 \frac{\partial \mathbf{u}}{\partial t} = -\nabla p' + \rho' \mathbf{g} + \frac{1}{c}[\mathbf{j} \times \mathbf{H}_0], \tag{1.1}$$

$$\frac{\partial p'}{\partial t} + (\mathbf{u}\nabla) p_0 = C_0^2 \left\{ \frac{\partial \rho'}{\partial t} + (\mathbf{u}\nabla)\rho_0 \right\}, \tag{1.2}$$

$$\frac{\partial \rho'}{\partial t} + (\mathbf{u}\nabla)\rho_0 + \rho_0 \operatorname{div} \mathbf{u} = 0, \tag{1.3}$$

$$\frac{m\omega_H}{e^2 N} \frac{[\mathbf{j} \mathrm{x} \mathbf{H}_0]}{H_0} + \mathbf{j}/\sigma - \frac{1}{\sigma_\perp} \frac{(\mathbf{j}\mathbf{H}_0)\mathbf{H}_0}{H_0^2} = \mathbf{E} + \frac{1}{c}[\mathbf{u} \mathrm{x} \mathbf{H}_0], \tag{1.4}$$

where $\mathbf{E}$ is the strength of the electric field; $\mathbf{H}_0$ is the intensity of the permanent Earth's magnetic field; $\mathbf{u}$ is the gas flow velocity; ρ' and p' are the perturbed values of density and pressure, constituting small deflections from the equilibrium values ρ_0 and p_0; $C_0^2 = \gamma_0(p_0/\rho_0)$ is the speed of sound (γ_0 is the heat capacity ratio at constant pressure and volume); $\mathbf{j}$ is the current density; N is the concentration of electrons; e and m are respectively the charge and the mass of the electron; ω_H is the gyrofrequency of electrons. The equations (1.1) and 1.3) are the evident corollaries of the well known equations of magnetohydrodynamics. The equation (1.2) is written in the assumption of approximate adiabaticity of the wave propagation process. Obviously, this assumption does not contradict the possibility of wave absorption searching. The correlation (1.4) represents the generalized Ohm law and is written in the form adopted in the work [10], where formulas for the conductivities $\sigma, \sigma_\perp$ are brought out (see below).

We neglected in the equations (1.1) — (1.3) the viscosity and we did not take into account the influence of heat conductivity; neither was the presence of ionospheric wind taken into account (the velocity $\mathbf{u}$ responds only to motions in the inner wave). The pressure p_0 satisfies the hydrostatic equilibrium equation $\nabla p_0 = \rho_0 \mathbf{g}$.

Let us introduce the Descartes system of coordinates, directing the axis z vertically upward. Then $\mathbf{g} = -g\mathbf{z}_0$, where $\mathbf{z}_0$ is the unitary vector in the direction of the axis z. The direction of the magnetic field will be characterized by the unitary vector $\tau = \mathbf{H}_0/H_0$ with projections on the axes x, y, z, respectively equal to $\cos\alpha$, $\cos\beta$, $\cos\gamma$. The projections of the velocity $\mathbf{u}$ will be denoted by u_x, u_y, u_z.

Estimating that the density and pressure p_0 are distributed according to the law

$$p_0 = p_{00}\exp(-z/H),\ \rho_0 = \rho_{00}\exp(-z/H), \qquad (1.5)$$

where H is the height of the uniform atmosphere; noting that $C_0^2 = \gamma_0 gH$), we may write the equation (1.1) in the following form:

$$\frac{\partial^2 \mathbf{u}}{\partial t^2} = C_0^2 \operatorname{grad}\operatorname{div}\mathbf{u} - g\nabla u_z + \mathbf{z}_0 g(1-\gamma_0)\operatorname{div}\mathbf{u} + \frac{1}{c\rho_0}\frac{\partial}{\partial t}[\mathbf{j}\times\mathbf{H}_0]. \quad (1.6)$$

When excluding the variables p' and ρ' we utilized the equations (1.2) and (1.3) and the correlations $\partial p_0/\partial z = -p_0/H$; $\partial \rho_0/\partial z = -\rho_0/H$ (see (1.5)).

From the character of the writing of the last term in (1.6) it is clear that the presence of current's $\mathbf{j}_\perp$ density component, transverse to the magnetic field H_0 is material. Subsequently, we shall take into account the validity at the F-layer height of the inequality

$$\nu_{im} \ll \Omega_H, \tag{1.7}$$

where ν_{im} is the collision frequency of ions with molecules; Ω_H is the gyro-frequency of ions. Then we shall have approximately from (1.4)

$$\mathbf{j}_\perp = \sigma_\perp \left(\mathbf{E} + \frac{1}{c}[\mathbf{u} \times \mathbf{H}_0] \right). \tag{1.8}$$

The first addend in the left-hand part of (1.4) may be rejected by the strength of (1.7). For the same reason we may substitute σ by $\sigma_\perp$ in the second addend of (1.4). The third addend in $\mathbf{j}_\perp$ does not contribute anything. For the transverse conductivity $\sigma_\perp$ and at limiting (1.7), we approximately have

$$\sigma_\perp = e^2 N \nu_{im} / M\Omega_H^2, \tag{1.9}$$

where M is the mass of the ion and N is the concentration of electrons.

Still another simplification is possible for large-scale disturbances, which is linked with the inequality

$$\mathbf{E} \ll \frac{1}{c} \; [\mathbf{u} \times \mathbf{H}_0].$$

In this case, from the equation for the electric field

$$\mathrm{rot}\,\mathrm{rot}\,\mathbf{E} = -\frac{4\pi}{c^2}\frac{\partial \mathbf{j}}{\partial t}$$

and taking into account (1.8), we have

$$\mathbf{E}_\perp \approx \frac{L^2}{c\delta_\perp}\frac{1}{T}[\mathbf{u} \times \mathbf{H}_0],$$

where L and T are the characteristic dimension and the time of the problem; $\delta_\perp = c^2/4\pi\sigma_\perp$ is the transverse magnetic viscosity. Introducing the Reynolds number $\mathrm{Re}_\perp = LV/\delta_\perp$, where $V = L/T$ is the velocity, we shall obtain the

estimate

$$\mathbf{E}_\perp \sim \frac{\mathrm{Re}_\perp}{c}[\mathbf{u} \times \mathbf{H}_0].$$

Hence we may neglect the field $\mathbf{E}$ in (1.8) provided $\mathrm{Re}_\perp \ll 1$. Note that an analogous criterion in the magnetohydrodynamic of istotropic media is well known [8]. In this case the accounting of conductivity anisotropy leads to the substitution of the isotropic magnetic viscosity factor δ by $\delta_\perp$ Let estimate the value of $\mathrm{Re}_\perp$. For the propagation velocity of disturbances we have $V \approx 2 \cdot 10^4$ cm/sec, and the scale L may be estimated to have a magnitude of the order 200 — 500 km. The value of the magnetic viscosity near the F-layer maximum is $\delta_\perp \sim 3 \cdot 10^{13}$, hence $\mathrm{Re}_\perp \sim (1 - 3) \cdot 10^{-2}$. Therefore, there is basis to estimate that $\mathrm{Re}_\perp \ll 1$. Neglecting the field $\mathbf{E}$ in (1.8), we shall finally have upon substitution into (1.6)

$$\frac{\partial^2 \mathbf{u}}{\partial t^2} = C_0^2 \operatorname{grad} \operatorname{div} \mathbf{u} - g \nabla u_z + (1 - \gamma_0) g z_0 \operatorname{div} \mathbf{u} + \frac{\sigma_\perp}{\rho_0 c^2} \frac{\partial}{\partial t} [[\mathbf{u} \times \mathbf{H}_0] \mathrm{x} \mathbf{H}_0]. \qquad (1.10)$$

The dependence of the conductivity $\sigma_\perp$ (1.9) on height is basically conditioned by the fact that $\nu_{im} \sim \rho_0$. Then, evidently, the coefficient in last addend of (1.10) at distances of the order of the height of uniform atmosphere H does not substantially vary and it will be considered as independent from z (and also from x and y). This remark refers also to the quantity C_0^2. Assuming that all the coefficients in (1.10) depend little on time, we may seek the solution in the form

$$\mathbf{u} = \mathbf{u}_0 \exp \{i\omega t - i\mathbf{K}\mathbf{r}\}.$$

As a result we arrive at the following vectorial correlation:

$$\omega^2 \mathbf{u} - [C_0^2 \mathbf{K} + i(1 - \gamma_0) g z_0] (\mathbf{K} \cdot \mathbf{u}) + i\mathbf{K} g u_z + i a [[\mathbf{u} \times \tau] \mathrm{x} \tau] = 0, \quad (1.11)$$

where

$$a = \omega V_A^2 / \delta_\perp = \frac{\sigma_\perp H_0^2}{\rho_0 c^2} \omega = \frac{N}{N_m} \frac{M}{M_m} \omega \nu_{im}. \qquad (1.12)$$

Here V_A is the Alfvén velocity; M_m is the mass of the molecule; N_m is the concentration of molecules. The last equality in (1.12) is written after taking into account (1.9). In spite of the simple character of the equation (1.11), its solution at $a \neq 0$ involves rather complex operations.

The case of strong magnetohydrodynamic absorption, as clearly unrealistic in the ionosphere, will not further arouse our interest. But at weak absorption we may obtain comparatively simple correlations.

Assume in the first approximation that $a = 0$. We then arrive at the well known dispersion equation for inner waves

$$\omega^4 - C_0^2\omega^2(K_x^2 + K_z^2) + i\gamma_0 g K_z \omega^2 + K_x^2 g^2(\gamma_0 - 1) = 0 \qquad (1.13)$$

Subsequently, we shall have for the ratio u_x / u_z

$$\frac{u_x}{u_z} = \frac{C_0^2 K_x K_z - i K_x g}{\omega^2 - C_0^2 K_x^2}. \qquad (1.14)$$

As in the work [2], when interpreting the events linked with shifting disturbances, we shall consider, in the first approximation, the quantity K_x to be real ($K_x = k_x$). Without limiting the generality we may assume that the propagation direction in the horizontal plane is parallel to the axis x. It is easy to establish from (1.13) that for real K_x, K_z will be complex. At the same time

$$K_z = k_z + \frac{i\gamma_0 g}{2C_0^2} = k_z + i/2H. \qquad (1.15)$$

For real k_x and k_z we shall obtain from (1.13), (1.15)

$$\omega^4 - \omega^2 C_0^2(k_x^2 + k_z^2) + (\gamma_0 - 1) g k_x^2 - \gamma_0^2 g^2 \omega^2 / 4C_0^2 = 0. \qquad (1.16)$$

It is clear from (1.15), (1.16) that the wave vector has a vertical as well as a horizontal component.

Subsequently, the amplitude values of motion velocity in the wave rise in the vertical direction according to the law $\exp(z/2H)$. We now shall find the value of absorption. At $a \neq 0$ we postulate that $K_x = k_x - iq_x$ and $K_z = k_z + i/2H - iq_z$, where $|q_x| \ll k_x$ and $|q_z| \ll |k_z + i/2H|$; it is shown below that the quantities q_x and q_z are complex. The absorption will be determined by the factor $\exp\{-\mathrm{Re}\,(q_x x + q_z z)\}$. Originating from (1.11) we shall obtain the system of equations for q_x and q_z :

../..

$$[C_0^2(2k_xu_x + k_zu_z) - ig(1-\gamma_0/2)u_z]q_x + C_0^2k_xu_zq_z = \\ = a[\sin^2\alpha\, u_x - \cos\alpha\cos\gamma\, u_z], \tag{1.17}$$

$$[C_0^2k_zu_x + ig\ (1-\gamma_0/2)u_x]q_x + C_0^2(2k_zu_z + k_xu_x)q_z = \\ = a[\sin^2\gamma\, u_z - \cos\alpha\cos\gamma\, u_x].$$

The values of the velocity components u_x and u_z in (1.17) are related to the case when the dissipation is absent ($a = 0$). Resolving the system (1.17) and utilizing (1.14), we obtain

$$q_x = aA/C, \quad q_z = aB/C,$$
$$A = C_0^2k_x[-\sin^2\gamma + d\cos\alpha\cos\gamma] + C_0^2[2k_z + dk_x] \times \\ \times [d\sin^2\alpha - \cos\alpha\cos\gamma],$$
$$B = [C_0^2(k_z + 2dk_x) - ig(1-\gamma_0/2)][\sin^2\gamma - d\cos\alpha\cos\gamma] - \\ - d[C_0^2k_z + ig(1-\gamma_0/2)][d\sin^2\alpha - \cos\alpha\cos\gamma], \tag{1.18}$$
$$C = (k_z + dk_x)[2C_0^2(k_z + dk_x) - ig(2-\gamma_0)],$$
$$d = [C_0^2k_xk_z - igk_x(1-\gamma_0/2)][\omega^2 - C_0^2k_x^2]^{-1}.$$

#2. - Magnetohydrodynamic Absorption of Shifting Disturbances.

Although the correlations (1.18) actually were obtained under certain simplifying assumptions, they still are rather difficult to read. However, if we make use of the well known facts concerning the shifting disturbances, significant simplifications are possible. Thus, we may use the limitation

$$b = \omega^2/k_x^2C_0^2 \ll 1, \tag{2.1}$$

which implies that the displacement velocities in the horizontal direction are substantially smaller than the speed of sound. Conducting the expansion by small parameter powers in (2.1), and after fairly simple, dut at the same time rather cumbersome transformations, we shall obtain the correlations

$$q_x = ak_xk_z^{-2}\omega^{-2}[k_x^2 + k_z^2 - (k_x\cos\gamma - k_z\cos\alpha)^2] \times \\ \times [1 - i\gamma_0k_zH/(2-\gamma_0)], \tag{2.2}$$
$$\operatorname{Im} q_z = k_zk_x^{-1}\operatorname{Im} q_x. \tag{2.3}$$

For $\operatorname{Re} q_z$ we obtain a relatively small value $\operatorname{Re} q_z \sim b \operatorname{Re} q_x$. The variations, linked with $\operatorname{Re} q_z \neq 0$, are of little substance by comparison with the contribution of the factor $\exp(z/2H)$, referred to above.

When passing from (1.8) to (2.2), (2.3), besides the condition (2.1) the inequality $2k_zH \gg 1$, which is usually well satisfied, has also been taken into account.

TABLE 1

z, км	V_ϕ = 100 м/sec	V_ϕ = 200 м/sec
200	$1,1\cdot10^{-8}$	$6\cdot10^{-9}$
250	$3,6\cdot10^{-8}$	$1,8\cdot10^{-8}$
300	$6,4\cdot10^{-8}$	$3,2\cdot10^{-8}$

As to the quantities $\mathrm{Im}\, q_x$ and $\mathrm{Im}\, q_z$, their relative contribution is more significant. However, this contribution is linked with the corrections for waves' propagation motion. Within the framework of the method applied (and factually) these corrections cannot modify substantially the character of the propagation and they are of little interest from the experimental point of view.

Since mainly horizontal shifts of irregularities are registered during observations, the greatest interest is offered by the estimates of the value of the absorption indicator $\mathrm{Re}\, q_x$, for which, when taking into account (1.12) and (2.2), we shall finally have

$$\mathrm{Re}\, q_x = \frac{NM\nu_{im}k_x}{N_mM_m\omega}[1 + k_x^2/k_z^2 - (\cos\alpha - k_x\cos\gamma/k_z)^2]. \qquad (2.4)$$

Note than in (2.4) the multiplier in brackets is always positive. It is something easy to ascertain if we utilize the Cauchy-Bunyakovskiy inequality [11]. As was to be expected $\mathrm{Re}\, q_x > 0$. Let us estimate in (2.4) the value of the multiplier $Q = NM\nu_{im}k_x / N_mM_m\omega$, which is not dependent upon the orientation of the magnetic field H_0. Table 1 gives the values of Q in cm^{-1} for various heights z corresponding to the ionospheric F-layer. We have taken for the phase velocity in the horizontal direction $V_\phi = \omega / k_x$ the characteristic values $V_\phi = 100-200$ м/ sec. When effecting the estimates we used the values of the collision frequency ν_{im} typical for the F-layer and for the concentration of electrons N — the data for the daytime ionosphere. In the nighttime the concentration N may decrease by one order and more, which will lead to an analogous decrease in the value of absorption.

The multiplier in (2.4) standing in brackets, depends on the orientation of the propagation direction relative to the field H_0. Let us compare the values of $\mathrm{Re}\, q_x$ for the propagation of disturbances along the meridian and along parallels. In the first case the direction of the magnetic meridian coincides approximately with the axis x and $\cos\beta = 0$. Then, from (2.4)

it ensues that

$$(\mathrm{Re}\, q_x)_M = Q(\sin\alpha + k_x \cos\alpha / k_z)^2. \tag{2.5}$$

For the propagation along parallels $\cos\alpha = 0$, and we shall have

$$(\mathrm{Re}\, q_x)_n = Q(1 + k_x^2 \sin^2\gamma / k_z^2). \tag{2.6}$$

From the results obtained in [3], we may derive the conclusion, that for disturbances under the condition (2.1) we must have $k_x \ll k_z$. Then, for very small α $(\mathrm{Re}\, q_x)_M$ is of the order $k_x^2 Q / k_z^2$, and at not too small α $(\mathrm{Re}\, q_s)_M = Q \sin^2\alpha$. Evidently, $(\mathrm{Re}\, q_x)_M < (\mathrm{Re}\, q_x)_n$.

Therefore, the absorption must be minimum in the N – S direction. It is true, however, that in moderate latitudes $(\mathrm{Re}\, q_x)_M / (\mathrm{Re}\, q_x)_n \sim 1$ (at meridional propagation the angle α coincides with the magnetic inclination). On the other hand, the quantity α decreases as it approaches the equator, and conditions are possible whereby $(\mathrm{Re}\, q_x)_M / (\mathrm{Re}\, q_x)_n \ll 1$. Thus, all the propagation directions of shifting disturbances, either at high or middle latitudes, are about equal in rights in regard to magnetohydrodynamic absorption. Consequently $\mathrm{Re}\, q_x \approx Q$ (the second multiplier in (2.2) for not too small α is near the unity).

Making use of Table 1 we may find the distances

$$L = 1/Q, \tag{2.7}$$

at which the amplitude of the wave decreases by e times. At the height $z = 200$ km with $V_\phi = 100$ and 200 m/sec. we have respectively $L = 800$ and 1600 km, while at 300 km $L \approx 150 - 300$ km for the same values of V_ϕ. The absorption is noticeable even at $z = 200$ km, without even speaking of greater heights. Near the F-layer maximum the appearance of large scale disturbances of the indicated type and with values $V_\phi = 100 - 200$ m/sec must, generally speaking, be fairly difficult on account of high absorption.

The estimates of absorption, brought out above, allow the qualitative assertion that the range of propagation of shifting disturbances does not usually exceed 2000 km [2].

As was shown above, the absorption at fixed heights must be more significant in daytime. This circumstance might influence the propagation range. However, it is difficult at present to derive specific conclusions

in this regard, for no measurements of the range at various times of the day have yet been carried out, at least to the best of our knowledge. Estimates of the values of Re q_x show that the rise of absorption is mainly linked with the increase of electron concentration. Thus, one may expect that this is precisely corroborated by the data of the Table, that is, the greatest absorption corresponds to heights near the F-layer maximum. This clarifies also the fact that most of shifting disturbances, with ranges of several thousand kilometers are registered at heights below that maximum ($z \sim 200 - 240$ km).

From (2.2) follows the conclusion that the absorption of shifting disturbances is minimum in meridional directions. It is natural to relate this conclusion with the assertion in a series of works [12, 13] that the N — S is the prevalent propagation direction of disturbances. At the same time, cases are noted [14, 15] of frequent disturbance propagation in other directions. Taking into account that the indicated minimum of absorption is expressed feebly in middle latitudes, it is difficult to speak in terms of coincidence of theory with experiment. It is quite possible that the prevalent propagation direction of disturbances in a specific direction is rather linked with other causes than the absorption (condition of wave excitation, carrying of charged particles by neutral ones and so forth).

*** THE END ***

Contract No.NAS-5-3760
Consultants & Designers, Inc.
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Translated by ANDRE L. BRICHANT
on 4 - 5 January 1965

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